Single Production of Fourth Family t' Quarks at LHeC

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Abstract

We study the single production of fourth-family t' quarks via the process $ep \to t'\nu$ at Large Hadron electron Collider (LHeC). We calculate the background and signal cross sections for the mass range 300-800 GeV. It is shown that the LHeC can discover single t' quark up to the mass of 800 GeV for the optimized mixing parameters.

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I. INTRODUCTION

The start-up of the Large Hadron Collider (LHC) will scan a new range of energy and mass to solve the well known unanswered questions in particle physics; especially concerned, two of them are flavor problem and electroweak symmetry breaking. The unification of these two problems is the major motivation to consider fourth family. In addition to the LHC, ep facility will also provide complementary information for new physics beyond the Standard Model (SM). The Large Hadron electron Collider (LHeC) [1] will consist of a new linear accelerator or a storage ring to collide electrons with energy of 70/140 GeV with the existing 7 TeV proton beam from the LHC. This will result in deep inelastic scattering interactions with a center of mass energy of 1.4/1.9 TeV, and with a luminosity of up to $10^{33}/10^{32}$ cm^{-2}s^{-1}, both significantly greater than the only previous electron-proton collider at HERA. The LHeC will also be expected to have sensitivity to new physics and new states of matter. It would give a possibility for polarized ep scattering to investigate the couplings of new fermions to the Standard Model (SM) fermions.

It is well known that the SM does not predict the number of fermion families. The fermion family replicants remain a mystery of the flavor problem. The discovery of a sequential fourth family may play an important role in understanding the flavor structure of the SM. Determination of the number of fermion families will be an important goal of the upcoming experiments at the LHC [2, 3, 4, 5, 6, 7], and further at the ILC and CLIC [8]. Meanwhile, the production of fourth family quarks via flavor changing neutral current interactions are investigated at future colliders [9, 10, 11, 12, 13].

The experiments at Tevatron have already constrained the masses of fourth family quarks. The collider detector at Fermilab (CDF) has searched strong pair production of t' with its associated anti-quark, each decaying to a W boson and a jet, with 2.8 fb^{-1} of data Run II of Tevatron setting a lower bound on mass of t' quark, $m_{t'} > 311$ GeV at 95% CL [14]. There seems to be some parameter space (mass vs. mixing angle) of the fourth family quarks which could be explored at future searches [2, 3, 4, 5, 7, 13].

In this study, we investigate the discovery potential of the LHeC for the single production of sequential fourth family t' quarks via the process $e^+p \to t'\bar{\nu}_e(e^-p \to \bar{t}'\nu_e)$ with the 70 GeV electron and 7 TeV proton beam energies. We have calculated the cross sections of signals and corresponding backgrounds. The decay widths and branching ratios of t' quark

are calculated in the mass range 300-800 GeV. All the calculations have been performed with CompHEP [15] by including the new interaction vertices.

II. SINGLE PRODUCTION AND DECAY OF t' QUARK

The extension of the SM is simply to add a sequential fourth family fermions where left-handed components transform as a doublet of $SU(2)_L$ and right-handed components as singlets. The interaction of the fourth family t' quark with the quarks q_i via the SM gauge bosons $(\gamma, g, Z^0, W^{\pm})$ is given by

$$\begin{aligned} L = & -g_e Q_t \bar{t}' \gamma^\mu t' A_\mu \\ & -g_s \bar{t}' T^a \gamma^\mu t' G^a_\mu \\ & -\frac{g}{2\cos\theta_W} \bar{t}' \gamma^\mu (g_V - g_A \gamma^5) t' Z^0_\mu \\ & -\frac{g}{2\sqrt{2}} V_{t' q_i} \bar{t}' \gamma^\mu (1-\gamma^5) q_i W^{\pm}_\mu + h.c. \end{aligned} \tag{1}$$

where g_e, g are the electro-weak coupling constants, and g_s is the strong coupling constant. A_μ, G_μ, Z^0_μ and $W^{\pm}_\mu$ are the vector fields for photon, gluon, Z^0-boson and $W^{\pm}$-boson, respectively. $Q_{t'}$ is the electric charge of fourth family quark t'; T^a are the Gell-Mann matrices. g_V and g_A are the vector and axial-vector type couplings of the neutral weak current with t' quark. Finally, the $V_{t'q}$ denotes the elements of extended 4×4 CKM mixing matrix which are constrained by flavor physics. In this study, we use the parametrization [6], $V_{t'd}$=0.063,$V_{t's}$=0.46,$V_{t'b}$=0.47, which were optimized for a 1σ deviation over the average values of the CKM matrix elements.

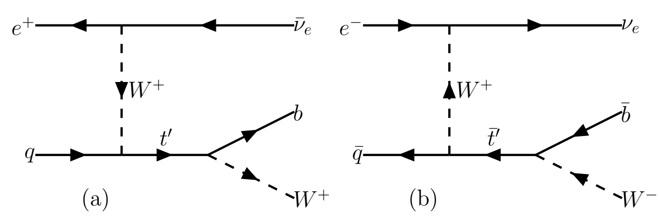

Figure 1: The diagrams relevant for single production of fourth family $t'(\bar{t}')$ quark at LHeC

The tree level Feynman diagrams for the single production of $t'(\bar{t}')$ quark and their subsequent decays are given in Fig. 1. The total decay widths of t' quark within the SM framework

are presented in Table I assuming the mass of t' quark between 300 and 800 GeV. For this parametrization t' branchings remain unchanged 51%(W^+b), 48%(W^+s), 0.9%(W^+d) in the considered mass range. In Fig. 2, we display the single production tree level cross-sections of the fourth generation t' (solid line) and $\bar{t}'$ (dot-dashed line) quarks depending on their masses at the LHeC with $\sqrt{s} = 1.4$ TeV. The cross sections of t' and $\bar{t}'$ quarks does not change significantly as seen in Fig. 2. Therefore, these two processes will be considered in our following analysis. We use the CTEQ6M [16] parton distribution function in our numerical calculations.

Table I: The total decay widths of t' quark depending on its mass values.

Mass (GeV)	Γ(GeV)
300	3.84
400	9.19
500	18.00
600	31.14
700	49.48
800	73.87

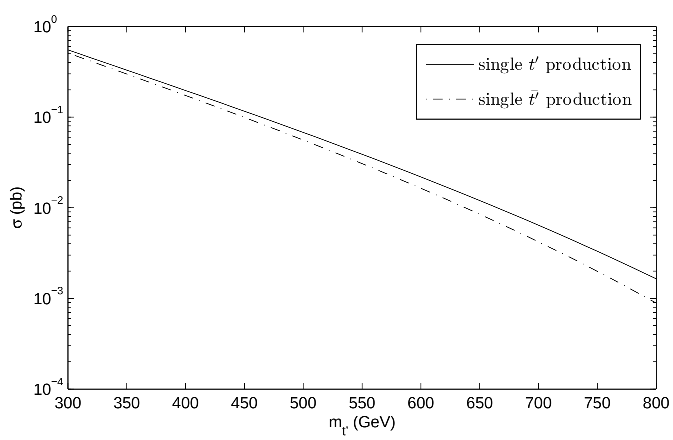

Figure 2: The total cross sections at the LHeC for the processes $e^+p \to t'\bar{\nu}_e$ (solid line) and $e^-p \to \bar{t}'\nu_e$(dot-dashed line) with $\sqrt{s} = 1.4$ TeV.

The transverse momentum distributions of the final state b-quark for the signal and background are shown in Fig. 3. The distribution of the final state b-quark from t' decays

is analyzed since b-quarks contribute substantially to the production mechanism. For a single t' quark production with a mass of 400 GeV, the p_T distribution shows a peak around 200 GeV, comparing this distribution with that of the corresponding background we could apply a p_T cut to reduce the background. For the final state $W^+b\nu_e$ we also plot the p_T distributions of W^+-boson and missing p_T for neutrino as shown in Figs. 4 and 5. As can be seen from Fig. 5, a cut on the missing transverse momentum $p_T^{miss} > 50$ GeV is required for the analysis.

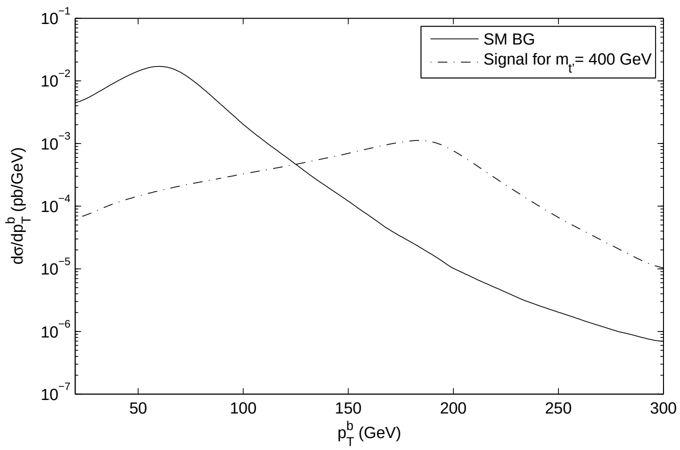

Figure 3: The differential cross section depending on the transverse momentum of the final state b quark for the subprocess $e^+p \to W^+b\bar{\nu}_e$. The solid line and dashed line correspond to the SM background and the signal for $m_{t'}$=400 GeV, respectively.

The signal and background events will show different rapidity distributions for the b-jet and $W^\pm$ boson in the final state as seen in Figs. 6 and 7. The invariant mass of W^+b system is shown in Fig. 8. The peaks show the t' signal with the mass of 400, 500 and 600 GeV.

III. ANALYSIS

In order to obtain the signal visible over the background we also apply an invariant mass cut $|m_{t'} - m_{W^+b}| < 10 - 20$ GeV according to the mass and the decay width of t' quark. Hence, we obtain a significant reduction on the cross section of the background. The background comes from SM events which yield exactly the same final state particles as the signal process. Here we consider the signal as a b-jet, the missing transverse energy (MET), and a W^+-boson, where it could be well reconstructed. Denoting σ_S and σ_B as the signal

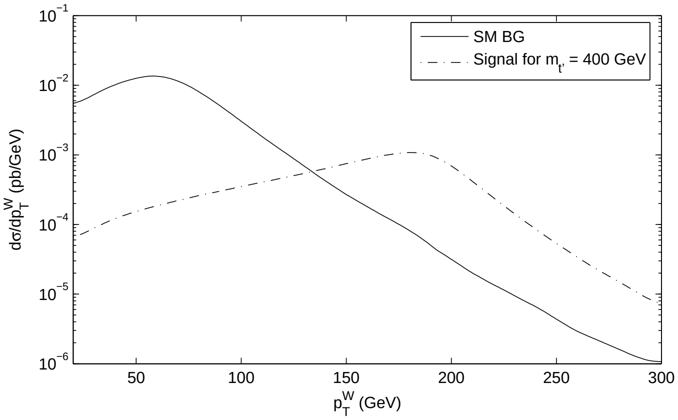

Figure 4: The differential cross section depending on the transverse momentum of the final state W^+-boson for the subprocess $e^+p \to W^+ b\bar{\nu}_e$ at the LHeC. The solid line and dashed line correspond to the SM background and signal for $m_{t'}$=400 GeV, respectively.

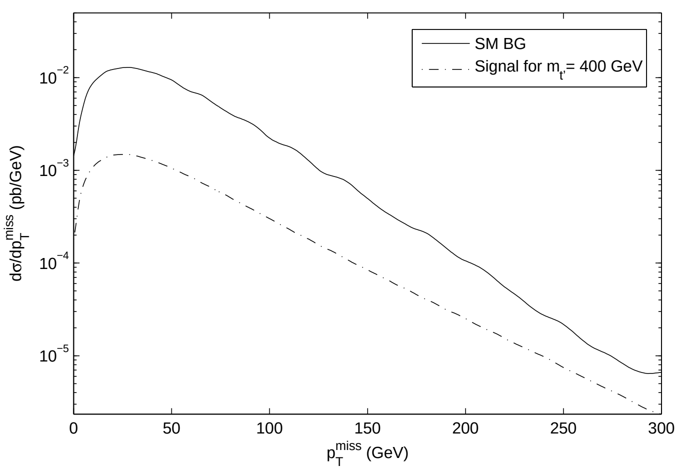

Figure 5: The differential cross section depending on the transverse momentum of the final state neutrino ν for the subprocess $ep \to Wb\nu$. The solid line and dashed line correspond to the SM background and signal for $m_{t'}$=400 GeV of this subprocess, respectively.

and background cross sections in the selected mass bins, we obtain the estimations for the statistical significance (SS) of the signal by assuming an integrated luminosity of $L_{int} = 10^4$ pb^{-1} per year,

$$SS = \sqrt{2L_{int}\epsilon[(\sigma_S + \sigma_B)\ln(1 + \sigma_S/\sigma_B) - \sigma_S]}.$$

The results for the signal significance of t' single production are given in Table II. While

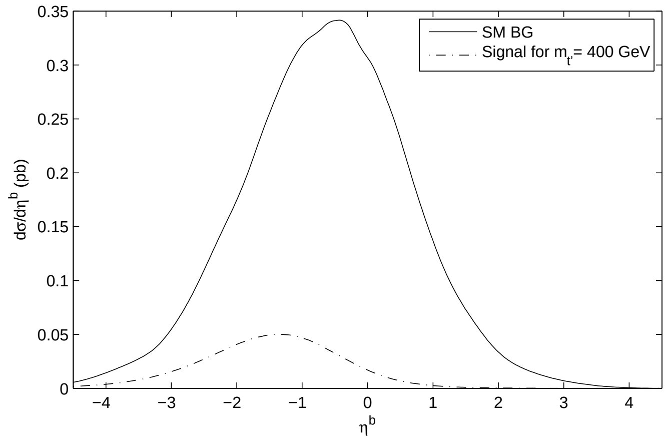

Figure 6: The rapidity distribution of final state b quark of the subprocess $e^+p \to W^+b\bar{\nu}_e$ for the SM background (solid line) and signal with $m_{t'}$=400 GeV (dot-dashed line).

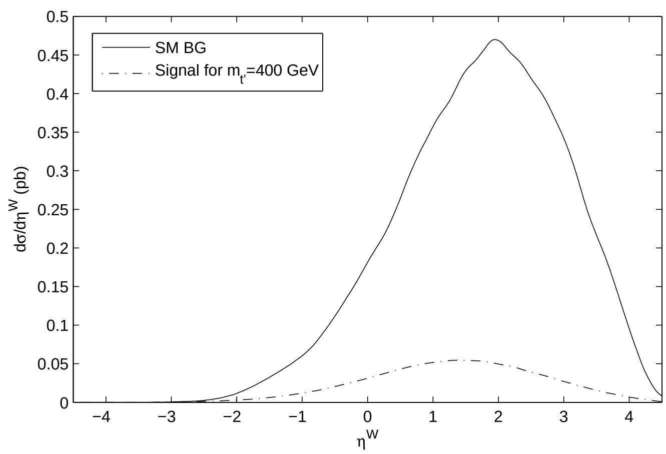

Figure 7: The rapidity distribution of final state W^+-boson of the subprocess $e^+p \to W^+b\bar{\nu}_e$ for the SM background (solid line) and signal with $m_{t'}$=400 GeV (dot-dashed line).

calculating the SS values we consider the leptonic decay of $W^\pm$ bosons with the branchings via $W^\pm \to l^\pm\nu_l$, where $l^\pm = e^\pm, \mu^\pm$ and we assume the b-tagging efficiency as $\epsilon = 60\%$. From Table II, we see that single t' quark can be observed at the LHeC with a mass in the range of 300-800 GeV provided optimal mixings with the other families are present.

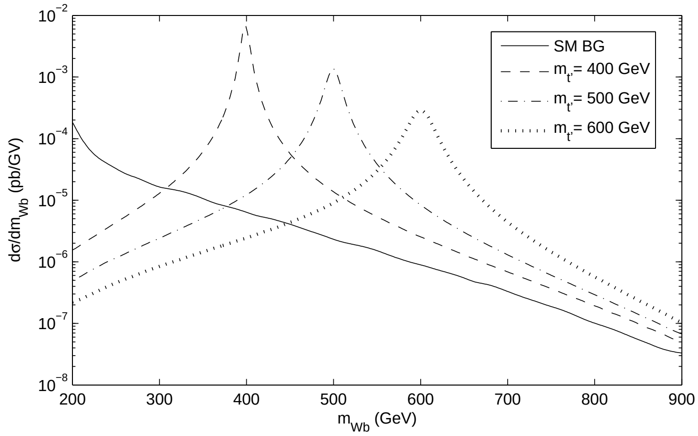

Figure 8: The invariant mass distribution for the SM background (solid line) and the Wb signal from t' decay for $m_{t'}$=400 GeV (dashed line), 500 GeV(dot-dashed line) and 600 GeV (dotted line).

Table II: The total cross section of signal (σ_s) and background (σ_b) for the subprocess $e^+p \to W^+b\bar{\nu}_e$ ($e^-p \to W^-\bar{b}\nu_e$) and its corresponding statistical significance (SS). While calculating the SS values we assume the $W^\pm$boson decays leptonically.

$m_{t'}$(GeV)	$\sigma_s(\bar{\sigma}_s)$(pb)	$\sigma_b(\bar{\sigma}_b)$(pb)	SS($\bar{SS}$)
300	1.607x10^1 (1.607x10^1)	9.012x10^{-5} (9.010x10^{-5})	4113.27 (4113.08)
400	7.503x10^{-2} (7.504x10^{-2})	1.230x10^{-4} (1.228x10^{-4})	1605.23 (1606.17)
500	3.012x10^{-2} (3.012x10^{-2})	1.163x10^{-4} (1.164x10^{-4})	544.23 (544.09)
600	1.120x10^{-2} (1.119x10^{-2})	8.894x10^{-5} (8.892x10^{-5})	171.39 (171.37)
700	3.845x10^{-3} (3.846x10^{-3})	5.997x10^{-5} (5.991x10^{-5})	49.15 (49.17)
800	1.210x10^{-3} (1.211x10^{-4})	1.047x10^{-4} (3.852x10^{-5})	8.35 (12.36)

IV. CONCLUSION

In the presence of the fourth family quarks, the LHC will discover them in pairs and measure their masses with a good accuracy. The single production may provide a unique measurement of the family mixing with the four families. The t' quarks can also be produced singly at the LHeC with large numbers if they have a large mixing with the other families of the SM. We have explored the single production of sequential fourth family t' quarks in ep collision at the LHeC energy with $\sqrt{s} = 1.4$ TeV. It is shown that the LHeC can discover

single t' quark up to 800 GeV with the optimized values of mixing parameters.

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